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Downlink and Uplink Transmission in K-tier Heterogeneous Cellular Network with Simultaneous Wireless Information and Power Transfer

Sunila Akbar*, Yansha Deng[†], Arumugam Nallanathan*, and Maged Elkashlan[†]

* Center for Telecommunications Research, King's College London, London, UK

[†] School of Electronic Engineering and Computer Science, Queen Mary University of London, London, UK

Abstract—The emerging fifth-generation (5G) wireless communication system is expected to provide higher capacity, seamless connectivity and reduced energy consumption to support data intensive multimedia applications. Simultaneous wireless information and power transfer (SWIPT) in heterogeneous cellular networks (HCNs) is a promising approach to offer efficient spectrum and energy utilization in the 5G system. In this paper, we develop a tractable model for joint uplink (UL) and downlink (DL) transmission in a K-tier HCN with SWIPT. We use the power splitting (PS) protocol where the receiver splits the received signal power in two parts for energy harvesting and information decoding. The harvested energy in the DL is utilized for UL information transmission. We derive the exact analytical expressions for the average received power and the outage probability for both DL and UL for the system design. Monte carlo simulations confirm the accuracy of the derived results, and numerical analysis reveal that SWIPT is a reasonably efficient technique to power the cellular users. In particular, we observe that with the increase of the picocell density, both the DL and the UL outage probability in macrocell decreases significantly. Moreover, the DL and the UL outage probability in a tier is shown to decrease with the increase of BS transmit power of its own tier.

Index Terms—SWIPT, energy harvesting, K-tier HCNs, stochastic geometry, outage probability

I. INTRODUCTION

The upsurge in the demand of multimedia applications, such as social networking and video calls, along with the emerging future applications, such as smart cities, health monitoring devices and driverless cars, future wireless networks will require much higher capacity. This explosive traffic growth, in turn, leads to fast energy consumption, and induces new mechanisms of energy control and reduction. HCNs featuring planned BSs, overlaid with micro, pico and femto BSs, can provide substantial gains in throughput and user-experience as compared to the conventional homogeneous networks [1–3]. Whereas radio frequency wireless power transfer (RF-WPT) is an emerging technology that enables the wireless devices to harvest energy from the RF signals for their information processing and transmission [4].

Lately, SWIPT has emerged as a novel research direction for decoding information and harvesting energy simultaneously from the same waveform. The concept of SWIPT was first presented from an information theoretic viewpoint to characterize the fundamental tradeoff between the transferred power and the information rate over the same channel [5, 6]. The

advanced applications of SWIPT were explored for the complex systems, including broadcast channels [7], and relaying networks [8]. Recharging mobiles and sensors via WPT for multi-cell wireless powered communication network (WPCN) was studied in [9], where the power beacons were deployed to power the mobiles for the UL information transmission.

In the HCNs, each tier differs in the transmit power of BSs, the path loss exponents, the spatial density and the SINR targets, so the practical cellular infrastructure deviates from the recognized regular hexagonal grid topology. Modelling and analysis of cellular networks using stochastic geometry provide tractable yet accurate performance bounds for multi-tier cellular networks [10]. In [11], modelling a K-tier HCN as Poisson point process (PPP) has been validated to be about as accurate as the idealized grid model for the coverage results. A crucial factor in modelling the HCNs is cell association which needs to be taken into account carefully. Therefore, different cell association schemes have been proposed, where the cell association in [11] and [12] are based on highest instantaneous SINR, and the maximum averaged biased-received-power, respectively. The existing research is mostly inclined towards the DL cell association with the only exclusions in [13, 14]. In [13], the UL association is based on the nearest BS amongst all tiers, while in [14], the DL and the UL association is performed by considering DL capacity and mobile UL power consumption respectively.

The main contributions of this work are summarized as follows:

- The analytical modeling of the HCN with SWIPT is presented based on stochastic geometry for efficient spectrum and energy utilization. We derive the analytical expressions for the average received power, the DL outage probability and the UL outage probability to provide useful guidelines for the system design. We use the nearest BS cell association for the DL where the user connects to the BS with lowest path loss, hence effective for harvesting energy for the efficient UL information transmission. We assume the user remains connected to the same BS in the UL, as in the DL.
- We study the effects of picocell BSs density, and BS transmit power on the DL and the UL outage probability. In particular, substantial improvement in the DL and the UL outage probability in the macrocell is observed with

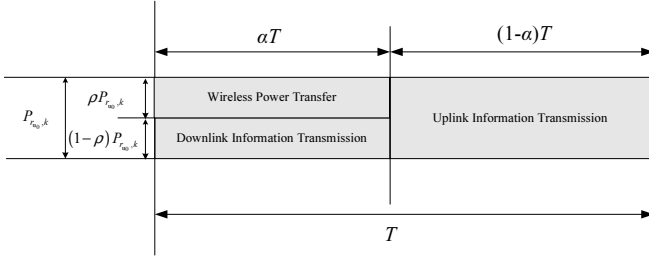


Fig. 1. Frame Structure

the increase of picocell BS density. Moreover, increasing the BS transmit power of a tier also results in decreased DL and UL outage in its own tier.

The rest of the paper is organized as follows. In Section II we present the system model for SWIPT in HCNs. In Section III, we derive per tier association probability, and the DL average received power. We then evaluate the network performance in terms of the DL and the UL outage probability in Section IV. Finally, the numerical results are discussed in Section V before the paper is concluded in Section VI.

II. SYSTEM DESCRIPTION

We model a K -tier HCN, where the BSs in each tier are spatially distributed in \mathbb{R}^2 as a homogenous Poisson point process (HPPP) Φ_j with density λ_j , where $j = 1, \dots, K$ is the index of the K tiers. We denote 'k' as the tier with which a typical user is associated. The mobile users are also modelled by an independent HPPP Φ_U with density λ_u . We assume that the density of users is high enough that each BS serves single user per channel. For simplicity, full frequency reuse scenario is considered. We consider Rayleigh fading model and the channel coefficients are assumed to be independent and identically distributed. For each tier we assume different path loss exponent as ℓ_j for $j = 1, \dots, K$.

A. Transmission Block Structure

Fig. 1 depicts the transmission block structure, we assume the transmission block time as $T = 1$, of which a fraction of the block time αT ($0 \leq \alpha \leq 1$), is used for the DL information transmission and the wireless power transfer, and the remaining portion $(1 - \alpha)T$ is used for the UL information transmission by using all the harvested energy from the first αT time.

We adopt the power splitting protocol in which the receiver splits the received power for harvesting energy and decoding the DL information. Assuming $P_{r_{u_0,k}}$ as the received power at the typical user in the k th tier, a fraction of the received power $\rho P_{r_{u_0,k}}$ ($0 \leq \rho \leq 1$) is used for harvesting energy, while the remaining $(1 - \rho)P_{r_{u_0,k}}$ is used for decoding information in the DL.

B. Cell Association

We consider the nearest BS association rule in the DL transmission of HCNs, where a typical user is associated to

the BS with the shortest distance. Therefore, for a typical user u_0 at the origin, the location of the serving BS in the k th tier, denoted as $x_{\hat{k}}$, is given as

$$x_{\hat{k}} = \underset{\{x \in \Phi_k\}_{k=1, \dots, K}}{\operatorname{argmin}} \|x\|.$$

In the UL information transmission, a typical user transmits information to the same serving BS.

C. Wireless Power Transfer

We assume the mobile user has a large storage mobile battery which stores the fraction of the received power ρP in the first αT time to ensure reliable UL transmission power in the remaining $(1 - \alpha)T$ time. To avoid the singularity caused by proximity between BSs and mobile users, a short range propagation model is used to ensure that the power received at the mobile user is finite [9].

The received power of a typical user u_0 at the origin in the k th tier can be written as

$$P_{r_{u_0,k}} = \underbrace{P_{t,b_{\hat{k}}} |h_{b_{\hat{k}}u_0}|^2 L_0 (\max\{\|x_{b_{\hat{k}}}\|, d\})^{-\ell_k}}_{I_{b_{\hat{k}}}} + \underbrace{\sum_{j=1}^K \sum_{b_j \in \Phi_j \setminus b_{\hat{k}}} P_{t,b_j} |h_{b_j u_0}|^2 L_0 (\max\{\|x_{b_j u_0}\|, d\})^{-\ell_j}}_{I_{b_x}}, \quad (1)$$

where L_0 is the path loss at a reference distance of 1 m, $d \geq 1$ is a constant, $b_{\hat{k}}$ is the serving BS at x_k , $h_{b_{\hat{k}}u_0}$ is the small-scale fading channel coefficient from the serving BS to a typical user, and $h_{b_j u_0}$ is the small-scale fading interfering channel coefficient from the BS at a location x_j to a typical user. All the channels are assumed to experience Rayleigh fading with unit mean from the serving/ interfering BSs.

The harvested energy at a typical user in the k th tier in the first αT time is $E_h^k = \eta \rho \mathbb{E}\{P_{r_{u_0,k}}\} \alpha T$, where $0 < \eta < 1$ is the energy conversion efficiency.

D. Downlink Information Transmission

In the DL information transmission, the fraction of the received power $(1 - \rho)P_{r_{u_0,k}}$ at the mobile user is used for decoding information in the αT time. The signal-to-interference-plus-noise ratio (SINR) of the DL information transmission is given by

$$SINR_k^{DL} = \frac{(1 - \rho) P_{t,b_{\hat{k}}} |h_{b_{\hat{k}}u_0}|^2 L_0 \|x_{b_{\hat{k}}}\|^{-\ell_k}}{(1 - \rho) \sum_{j=1}^K \sum_{b_j \in \Phi_j \setminus b_{\hat{k}}} P_{t,b_j} |h_{b_j u_0}|^2 L_0 \|x_{b_j u_0}\|^{-\ell_j} + \sigma^2}, \quad (2)$$

where σ^2 is the noise power at the user.

E. Uplink Information Transmission

We assume that the users keep associated with the serving BSs that powered them in the first αT time, and use the harvested energy to transmit the UL information in the $(1-\alpha)T$ time. The UL transmit power for the typical user in the k th tier is defined as $P_{t_{u_0},k} = \frac{E_h^k}{(1-\alpha)T}$. We the help of the Slivnyak's theorem [10], we characterize the SINR of the UL transmission for a typical BS at the origin, which is given by

$$\text{SINR}_k^{UL} = \frac{\phi \mathbb{E}\{P_{r_{u_0},k}\} |h_{u_0,b_{\hat{k}}}|^2 L_0 \|x_{u_0,b_{\hat{k}}}\|^{-\ell_k}}{\sum_{j=1}^K \sum_{u_j \in \Phi_j \setminus u_0} \phi \mathbb{E}\{P_{r_{u_j},j}\} |h_{u_j,b_{\hat{k}}}|^2 L_0 \|x_{u_j,b_{\hat{k}}}\|^{-\ell_j} + \delta^2}, \quad (3)$$

where $\phi = \frac{\eta\rho\alpha}{(1-\alpha)}$, $h_{u_0,b_{\hat{k}}}$ is the small-scale fading channel coefficient from the user u_0 to its serving typical BS, $h_{u_j,b_{\hat{k}}}$ is the small-scale fading interfering channel coefficient from the user u_j to a typical BS, Φ_j represents the interfering users in the j th tier, and δ^2 is the noise power at the BS.

III. EXACT ANALYSIS OF DOWNLINK POWER TRANSFER

In this section, we derive the analytical expression for the average received power of a typical user.

A. Nearest BS Cell Association

In order to facilitate the analysis, we first write the per tier association probability, and the PDF of distance between the typical user and the nearest serving k th tier BS for nearest BS is given by [12].

The probability that a typical MU is associated with the k th tier BS is

$$\Lambda_k = \left(1 + \frac{\sum_{j=1, j \neq k}^K \lambda_j}{\lambda_k}\right)^{-1}. \quad (4)$$

The PDF of the distance between a typical user and its serving BS in the k th tier is derived as

$$f_{\|x_{b_{\hat{k}}}\|}(x) = 2\kappa x \exp\{-\kappa x^2\}, \quad (5)$$

where

$$\kappa = \pi \sum_{j=1}^K \lambda_j. \quad (6)$$

B. Average Received Power

In the DL HCN, we assume that the mobiles have large energy storage capacity, thus the active mobiles can transmit with reliable transmission power in the UL. To determine the transmit power of a typical user in the k th tier $\phi \mathbb{E}\{P_{r_{u_0},k}\}$, we first derive the average received power at a typical user in the k th tier in the following theorem.

Theorem 1. The average received power at the typical user in the k th tier is given by

$$\begin{aligned} & \mathbb{E}\{P_{r_{u_0},k}\} \\ &= P_{t,b_{\hat{k}}} L_0 \left[\left[d^{-\ell_k} \left(1 - \exp(-\kappa d^2)\right) \right] + \left[\kappa^{\frac{\ell_k}{4}} d^{-\frac{\ell_k}{2}} \exp\left(-\frac{1}{2}\kappa d^2\right) \right. \right. \\ & \quad \left. \left. W_{-\frac{\ell_k}{2}, \frac{1}{2}}\left(1 - \frac{\ell_k}{2}\right)(\kappa d^2)\right) \right] + 2\pi L_0 \sum_{j=1}^K P_{t,b_j} \lambda_j \left[\left[\frac{\ell_j d^2}{2d^{\ell_j}(\ell_j - 2)} \right. \right. \right. \\ & \quad \left. \left. \left(1 - \exp(-\kappa x^2)\right) \right] - \left[\frac{1}{2d^{\ell_j}(\kappa)} \gamma(2, \kappa) \right] + \left[\frac{\pi \left(\sum_{j=1}^K \lambda_j\right)^{\frac{3\ell_j-2}{4}}}{(\ell_j - 2)} \right. \right. \\ & \quad \left. \left. d^{-\frac{\ell_j}{2}+1} \exp\left(-\frac{1}{2}\kappa x^2\right) W_{\frac{\ell_j-2}{4}, \frac{1}{2}}\left(-\frac{\ell_j}{2}\right)(\kappa d^2)\right) \right] \right], \end{aligned} \quad (7)$$

where κ is given in (6), $W_{\lambda,\mu}(z)$ is Whittaker function [15], and $\gamma(a, x)$ is lower incomplete gamma function [15].

Proof: From (1), we first derive the expectation of $I_{b_{\hat{k}}}$ as

$$\begin{aligned} \mathbb{E}\{I_{b_{\hat{k}}}\} &= \mathbb{E}\left\{P_{t,b_{\hat{k}}} |h_{b_{\hat{k}}}|^2 L_0 \left(\max\{\|x_{b_{\hat{k}}}\|, d\}\right)^{-\ell_k}\right\} \\ &\stackrel{(a)}{=} P_{t,b_{\hat{k}}} L_0 \left[\int_0^d d^{-\ell_k} f_{\|x_{b_{\hat{k}}}\|}(x) dx + \int_d^\infty x^{-\ell_k} f_{\|x_{b_{\hat{k}}}\|}(x) dx \right], \end{aligned} \quad (8)$$

where (a) follows from the fact that $|h_{b_{\hat{k}}}|^2 \sim \exp(1)$. Substituting the PDF of $\|x_{b_{\hat{k}}}\|$ into (8), and simplifying the resulting equation using [15, eq. 3.381.1] and [15, eq. 3.381.6], we derive $\mathbb{E}\{I_{b_{\hat{k}}}\}$. Further, the expectation of I_{b_x} is derived as

$$\begin{aligned} \mathbb{E}\{I_{b_x}\} &= \sum_{j=1}^K \mathbb{E}_h\{P_{t,b_j} L_0 |h_{b_j u_0}|^2\} \mathbb{E}_x\left\{\mathbb{E}_{\Phi_j}\left\{\sum_{b_j \in \Phi_j \setminus b_{\hat{k}}} \right. \right. \\ & \quad \left. \left. \left(\max\{\|x_{b_j u_0}\|, d\}\right)^{-\ell_j}\right\}\right\}. \end{aligned} \quad (9)$$

The interfering BSs need to be located outside a disc of a radius $r_{\min} = \|x_{b_{\hat{k}}}\|$ to satisfy the nearest BS cell association. Applying the Campbell's Theorem [16] to (9), and utilizing the fact that $|h_{b_j u_0}|^2 \sim \exp(1)$, we derive

$$\begin{aligned} \mathbb{E}\{I_{b_x}\} &= \sum_{j=1}^K 2\pi P_{t,b_j} L_0 \lambda_j \left[\int_0^\infty \left[\int_{r_{\min}}^\infty (\max\{x_0, d\})^{-\ell_j} r dr \right] \right. \\ & \quad \left. f_{\|x_{b_{\hat{k}}}\|}(x) dx \right]. \end{aligned} \quad (10)$$

Substituting the PDF of $\|x_{b_{\hat{k}}}\|$ from (5) into (10), and solving the resulting equation by using [15, eq. 3.381.1] and [15, eq. 3.381.6], we obtain $\mathbb{E}\{I_{b_x}\}$. Combining the equations of $\mathbb{E}\{I_{b_x}\}$ and $\mathbb{E}\{I_{b_{\hat{k}}}\}$, we derive (7).

IV. PERFORMANCE EVALUATIONS: EXACT ANALYSIS

The performance of the DL and the UL transmission of the HCN is characterized by the outage probability, which is equivalent to the cumulative distribution function (CDF) of SINR for a randomly selected user in the network.

A. Downlink Outage Probability

The DL outage probability in the HCNs is given by

$$P_{out}^{DL} = \sum_{k=1}^K \Lambda_k^{DL} P_{out,k}^{DL}, \quad (11)$$

where Λ_k^{DL} is the probability that a typical user is associated to the k th tier, which is given as in Lemma 1, and $P_{out,k}^{DL}$ is the DL outage probability of a typical user associated with k th tier in the downlink. For a target SINR β and a typical user at a distance $\|x_{b_{\hat{k}},u_0}\|$ from its associated BS, the outage probability for the DL is defined as

$$\begin{aligned} P_{out,k}^{DL}(R_s) &= \mathbb{E}_{\|x_{b_{\hat{k}},u_0}\|} \left\{ \Pr \left(\alpha \ln \left(1 + \text{SINR}_k^{DL} \left(\|x_{b_{\hat{k}},u_0}\| \right) \right) \leq R_s \right) \right\} \\ &= \mathbb{E}_{\|x_{b_{\hat{k}},u_0}\|} \left\{ \Pr \left(\text{SINR}_k^{DL} \left(\|x_{b_{\hat{k}},u_0}\| \right) \leq \beta \right) \right\}, \end{aligned} \quad (12)$$

where R_s is the rate threshold, and

$$\beta = e^{R_s/\alpha} - 1 \quad (13)$$

Theorem 2. The downlink outage probability of a typical user associated with the k th tier is derived as

$$\begin{aligned} P_{out,k}^{DL}(R_s) &= 1 - 2\kappa \int_0^\infty x \exp \left\{ -\sigma^2 \beta \Omega_k^{DL} \|x_{b_{\hat{k}},u_0}\|^{\ell_k} \right. \\ &\quad \left. - \kappa (\vartheta_j - x^2) \right\} dx, \end{aligned} \quad (14)$$

where

$$\vartheta_j = \mathcal{U}_{j,k}^{2/\ell_j} \int_{\mathcal{U}_{j,k}^{-2/\ell_j} x^2}^\infty \frac{1}{1+z^{\ell_j/2}} dz, \quad (15)$$

$$\Omega_k^{DL} = \left((1-\rho) P_{t,b_j} L_0 \right)^{-1}, \quad (16)$$

$$\mathcal{U}_{j,k} = \beta (P_{t,b_j} / P_{t,b_{\hat{k}}}) x^{\ell_k}, \quad (17)$$

β and κ are given in (13) and (6), respectively.

Proof: We express (12) in terms of complementary cumulative distribution function (CCDF) of SINR_k^{DL} as

$$P_{out,k}^{DL}(R_s) = \mathbb{E}_{\|x_{b_{\hat{k}},u_0}\|} \left\{ 1 - \left[\Pr \left(\text{SINR}_k^{DL} \left(\|x_{b_{\hat{k}},u_0}\| \right) > \beta \right) \right] \right\}. \quad (18)$$

Substituting SINR_k^{DL} from (2) into (18), we express

$$\begin{aligned} P_{out,k}^{DL}(R_s) &= 1 - \int_0^\infty \Pr \left[\frac{|h_{b_{\hat{k}},u_0}|^2 \|x_{b_{\hat{k}},u_0}\|^{-\ell_k}}{(I_{b_x}^{DL} + \sigma^2) \Omega_k^{DL}} > \beta \right] \\ &\quad f_{\|x_{b_{\hat{k}},u_0}\|}(x) dx, \end{aligned} \quad (19)$$

where Ω_k^{DL} is given in (16), $I_{b_x}^{DL} = \sum_{j=1}^K I_{b_j}^{DL}$, and $I_{b_j}^{DL} = \sum_{b_j \in \Phi_j \setminus b_{\hat{k}}} (1-\rho) P_{t,b_j} |h_{b_j,u_0}|^2 L_0 \|x_{b_j,u_0}\|^{-\ell_j}$.

In (19), the CCDF of a typical user at a distance x from its associated BS in k th tier is given as

$$\begin{aligned} &\Pr \left[\frac{|h_{b_{\hat{k}},u_0}|^2 \|x_{b_{\hat{k}},u_0}\|^{-\ell_k}}{(I_{b_x}^{DL} + \sigma^2) \Omega_k^{DL}} > \beta \right] \\ &= \mathbb{E}_{I_{b_x}} \left\{ \Pr \left[|h_{b_{\hat{k}},u_0}|^2 > (I_{b_x}^{DL} + \sigma^2) \beta \Omega_k^{DL} \|x_{b_{\hat{k}},u_0}\|^{-\ell_k} \right] | I_{b_x}^{DL} \right\} \\ &\stackrel{(a)}{=} \int_0^\infty \exp \left\{ -(\Omega_k^{DL} + \sigma^2) \beta \Omega_k^{DL} \|x_{b_{\hat{k}},u_0}\|^{-\ell_k} \right\} \\ &\quad d \Pr \left(I_{b_x}^{DL} \leq \Omega_k^{DL} \right) \\ &\stackrel{(b)}{=} \exp \left\{ -\sigma^2 \beta \Omega_k^{DL} \|x_{b_{\hat{k}},u_0}\|^{\ell_k} \right\} \mathcal{L}_{I_{b_x}^{DL}} \left(\beta \Omega_k^{DL} \|x_{b_{\hat{k}},u_0}\|^{-\ell_k} \right), \end{aligned} \quad (20)$$

where (a) follows from the fact that $|h_{b_{\hat{k}},u_0}|^2 \sim \exp(1)$, and (b) follows from the definition of Laplace transform. Using generating functional of HPPP in [16] and $\mathcal{L}_{I_{b_x}}(s) = \prod_{j=1}^K \mathcal{L}_{I_{b_j}}(s)$, we derive

$$\begin{aligned} \mathcal{L}_{I_{b_x}^{DL}}(s) &\stackrel{(a)}{=} \exp \left\{ 2\kappa \int_x^\infty \left(1 - \mathbb{E}_h \left\{ -s(1-\rho) P_{t,b_j} \right. \right. \right. \\ &\quad \left. \left. |h_{b_j,u_0}|^2 L_0 \|x_{b_j,u_0}\|^{-\ell_j} \right\} \right) y dy \right\} \\ &\stackrel{(b)}{=} \exp \left\{ 2\kappa \int_x^\infty \left(1 - \frac{1}{1 + \mathcal{U}_{j,k} y^{-\ell_j}} \right) y dy \right\}, \end{aligned} \quad (21)$$

where the integration limits in (a) follows from the fact that the nearest interferer in j th tier is at least at $r_{\min} = x$, and (b) follows from the fact that $|h_{b_j,u_0}|^2 \sim \exp(1)$. $\mathcal{U}_{j,k}$, κ and ϑ_j are given in (17), (6) and (15), respectively. Simplifying (21) by employing change of variables $z = \mathcal{U}_{j,k}^{-2/\ell_j} y^2$ and substituting into (20), we derive

$$\Pr \left(\text{SINR}_k^{DL} \left(\|x_{b_{\hat{k}},u_0}\| \right) > \beta \right) = \exp \left\{ -\sigma^2 \beta \Omega_k^{DL} \|x_{b_{\hat{k}},u_0}\|^{\ell_k} - \kappa \vartheta_j \right\}, \quad (22)$$

Plugging (22) and (5) into (18), we obtain Theorem 2.

B. Uplink Outage Probability

The UL outage probability in the HCNs is given by

$$P_{out}^{UL} = \sum_{k=1}^K \Lambda_k^{UL} P_{out,k}^{UL}, \quad (23)$$

where Λ_k^{UL} is the probability that a typical user is associated to the k th tier in (4), and $P_{out,k}^{UL}$ is the UL outage probability of a typical user associated with k th tier. For a typical user at a distance $\|x_{u_0,b_{\hat{k}}}\|$ from its associated BS and a target SINR β , the UL outage probability is defined as

$$\begin{aligned} P_{out,k}^{UL}(R_s) &= \mathbb{E}_{\|x_{b_{\hat{k}},u_0}\|} \left[\Pr \left((1-\alpha) \ln \left(1 + \text{SINR}_k^{UL} \left(\|x_{b_{\hat{k}},u_0}\| \right) \right) \leq R_s \right) \right] \\ &= \mathbb{E}_{\|x_{b_{\hat{k}},u_0}\|} \left[\Pr \left(\text{SINR}_k^{UL} \left(\|x_{b_{\hat{k}},u_0}\| \right) \leq \Delta \right) \right]. \end{aligned} \quad (24)$$

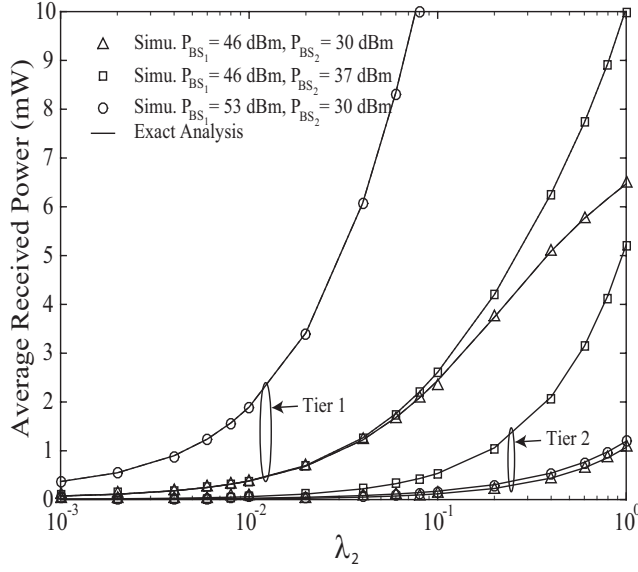


Fig. 2. Average Received Power in a two-tier HCN with parameters $\ell_1 = 3.8$, $\ell_2 = 3.5$

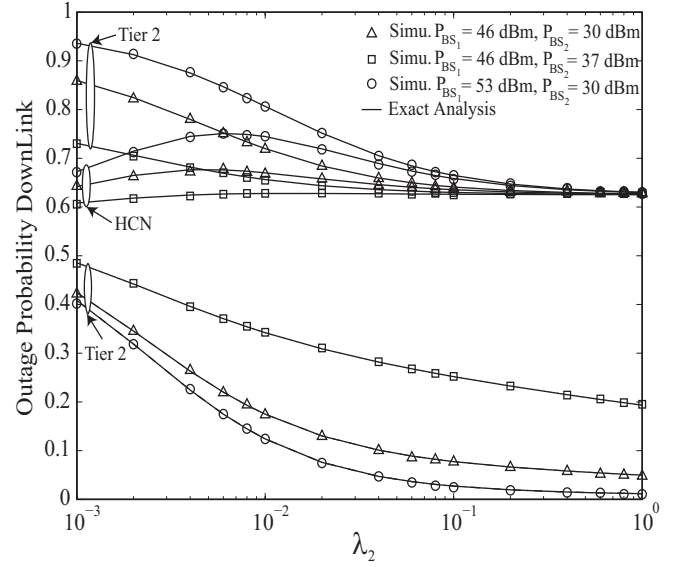


Fig. 3. Downlink Outage Probability in a two-tier HCN with parameters $\ell_1 = 3.8$, $\ell_2 = 3.5$ and $R_s = 0.5$ nats/s/Hz

where

$$\Delta = e^{R_s/(1-\alpha)} - 1 \quad (25)$$

Theorem 3. The UL outage probability of a typical user associated with the k th tier is derived as

$$P_{out,k}^{UL}(R_s) = 1 - 2\kappa \int_0^\infty x \exp\left\{-\delta^2 \Delta \Omega_k^{UL} x^{\ell_k} - \sum_{j=1}^K \left(\zeta_{k,j}^{UL} x^{\frac{2\ell_k}{\ell_j}} \Delta^{\frac{2}{\ell_j}} + \pi \lambda_j x^2 \right)\right\} dx, \quad (26)$$

where

$$\Omega_k^{UL} = (\phi \mathbb{E}\{P_{r_{u_0},k}\} L_0)^{-1}, \quad (27)$$

$$\zeta_{k,j}^{UL} = \pi \lambda_j \left(\frac{\mathbb{E}\{P_{r_{u_j},j}\}}{\mathbb{E}\{P_{r_{u_0},k}\}} \right)^{\frac{2}{\ell_j}} \Gamma\left(1 + \frac{2}{\ell_j}\right) \Gamma\left(1 - \frac{2}{\ell_j}\right), \quad (28)$$

Δ and κ are given in (25) and (6), respectively.

Proof: The proof follows the same steps as of Theorem 2.

V. NUMERICAL RESULTS

In this section, we use the derived expressions of the average received power, and the DL and the UL outage probability to evaluate system performance. The analytical results are validated by Monte Carlo simulations where BSs are deployed according to the presented model, and the user is fixed at the origin. For all the numerical analysis, the path loss is taken as $L_0 = -38.5$ dB at 1 meter, thermal noise at the user is taken as $\sigma^2 = -104$ dB, and thermal noise at the BS is taken as $\delta^2 = -104$ dB for 10 MHz bandwidth. In all the figures,

red lines represent the macrocell, green lines represent the picocell, and blue lines represent the overall network.

In Fig. 2 we plot the average received power at the typical user versus the density of picocell λ_2 for various transmit powers at each BS. We observe the increase in the average received power of the user with increased λ_2 . With the large number of picocell BSs, the harvested energy would be more which leads to increased average received power. We also observe that the average received power of the user in each tier increases with the increase in the BS transmit power.

Fig. 3 examines the effect of picocell BS density λ_2 and BS transmit power of each tier on the DL outage probability. It can be observed that with the increase of λ_2 , the DL outage probability of a typical user decreases in both the tiers. Surprisingly, irrespective of the decrease in the outage in both the tiers, the increase in λ_2 seems to have approximately no impact on the overall outage of the network. The mentioned trends could be explained as below:

- The increased λ_2 causes the probability of the user to associate with the picocell to be higher than the probability of the user to associate with the macrocell as in (4). This implies that with the increase in λ_2 , the users associated to the macrocell will be few, and the only ones which are in much close proximity to the macrocell BS as per cell association criterion, thereby receiving high signal power which ultimately results in the less outage in the macrocell.
- With the increase of λ_2 the users will be more closer to the associated picocell BS, thereby receiving high signal power which ultimately results in less outage in the picocell.
- Adding picocell BSs increases the interference and de-

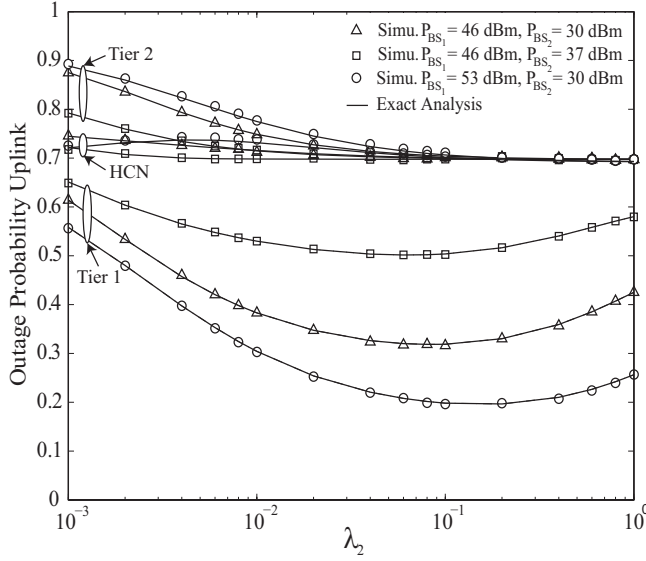


Fig. 4. Uplink Outage Probability in a two-tier HCN with parameters $\ell_1 = 3.8$, $\ell_2 = 3.5$ and $R_s = 0.5$ nats/s/Hz

creases the macrocell association probability, therefore the overall outage probability is not strongly affected by the increased λ_2 .

On the other hand, increasing the BS transmit power in either tier results in the less outage in its own tier, in contrast to the more outage in the other tier. This can be explained by (2), the increased transmit power implies greater signal strength at its associated user causing high $SINR_k^{DL}$, which in turn results into the less outage. Contrarily, the increased transmit power results in greater interference at the other tier's user causing low $SINR_k^{DL}$, which in turn results into the more outage.

Fig. 4 plots the UL outage probability versus the picocell BS density λ_2 for various transmit powers at each tier's BSs. The UL outage probability follows the same trends as the DL and can be explained in the similar fashion with an exception as explained below.

- With increase in λ_2 , the UL outage probability of a typical macrocell BS decreases uptill a certain λ_2 , after which it increases due to the increased interference. The increased interference results from the fact that with the large number of picocell BSs, the users harvest greater energy as shown in Fig. 2, and transmit with higher power in the UL.

VI. CONCLUSIONS

In this paper, we have presented a tractable model for SWIPT in HCNs, where the mobile user harvests energy and decodes information in the DL and uses that harvested energy for UL information transmission. Relying on stochastic geometry, we derive the exact analytical expressions for the DL average received power, the DL outage probability and

the UL outage probability of the proposed system. We have shown that SWIPT can be an efficient technique to power the users in HCNs towards energy and spectrum efficient 5G wireless communication system. Furthermore, we have shown the improvement in the network performance with the increase of the picocell BS density and the BS transmit power of each tier. Future work will include the analysis for a battery free user along with the optimization of the network parameters for improved network performance.

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